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On the Assessment of Drone Noise for Sustainable Urban Air Mobility Operations †

Marco Rinaldi *, Saeed Maghsoodi and Stefano Primatesta

Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca Degli Abruzzi 24, 10129 Torino, Italy

* Correspondence: marco_rinaldi@polito.it

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Abstract

Drone noise-induced human annoyance is emerging as one of the main barriers to socially acceptable large-scale urban air mobility (UAM) operations, which have the potential to revolutionize urban transportation systems in the next few decades. This paper investigates the state-of-the-art technology in the assessment of drone noise and its impact on individuals, focusing on measurement and evaluation methodologies, as well as subjective evaluations. Various acoustic metrics are reviewed to characterize drone noise, including sound pressure levels, spectral analysis, and psychoacoustic parameters such as loudness and annoyance. Preliminary experimental investigations to identify key frequencies and tonal components that significantly contribute to drone noise-induced public annoyance are also discussed. Interdisciplinary approaches integrating pure technical acoustics, human perception, and subjectivity emerge as promising solutions for a comprehensive understanding of drone noise effects. Finally, a preliminary framework for drone noise assessment towards noise-aware UAM operations is proposed.

Keywords: drone noise; noise assessment; sustainable UAM; low-noise UAV operations

1. Introduction

The widespread application of UAM services is highly challenged by noise pollution concerns [1–3]. Unlike traditional noise sources, drones produce high-frequency tonal components and broadband noise, resulting from the rapid rotation of propellers and complex aerodynamic interactions [4–6]. These characteristics make drone noise more noticeable and often more annoying to humans compared to other environmental noises [7]. This can negatively affect people's daily activities, increase stress, and disrupt quiet environments, particularly in rural or suburban areas. These challenges highlight the urgent need for comprehensive research into drone noise assessment and mitigation, including low-level UAV design and control [6–8], path planning and navigation [8–10], high-level operations planning [11], and psychoacoustics investigations [12–15]. This paper is organized as follows. A critical review of state-of-the-art drone noise assessment methods is proposed in Section 2. Section 3 discusses the impacts of drone noise on humans and presents the emerging trends in correlating drones' characteristics, operating conditions, and noise emissions. Section 4 introduces a preliminary drone noise assessment framework towards noise-aware urban air mobility operations. Conclusions and future research directions are drawn in Section 5.

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2. Noise Assessment Methods

The accurate measurement and evaluation of drone noise are critical in understanding its impacts and developing effective mitigation strategies. Researchers have adopted several methodologies, each offering unique insights and presenting specific limitations. The methodologies that form the backbone of current advancements in drone noise analysis are listed as follows: sound level meters [16–18]; backpropagation of sound levels [16–18]; noise directivity analysis [14]; surveys and subjective assessments [15]; psychoacoustic evaluations [12–14]; and emerging approaches [19,20]. Sound level meters (SLMs) are among the most widely used tools for noise measurement. They provide quantitative data on pound pressure levels (SPLs) across various frequency ranges, enabling researchers to identify key tonal and broadband noise components generated by drones. These measurements are typically conducted in controlled environments, such as anechoic chambers, or in field conditions to capture real-world scenarios. Despite being effective for objective noise quantification, SLMs do not capture subjective factors like human annoyance or the perception of tonal components, requiring supplementary methodologies. Backpropagation methods are essential to estimate source noise levels accurately at an arbitrary distance from the drone. This technique involves applying mathematical corrections for spherical spreading, atmospheric absorption, and ground reflections, as outlined in ISO 9613-2:1996 [21]. By measuring noise at a known distance, researchers can use backpropagation formulas to calculate the equivalent noise at the source. This approach ensures the standardized characterization of drone noise independently of environmental variables. For instance, backpropagation models account for temperature, humidity, and terrain factors to provide a consistent noise profile for comparative studies. The fundamental steps in backpropagation include the following: data collection (measurement of SPLs at specific distances from the noise source using calibrated SLMs); correction factors (application of corrections for geometric spreading, atmospheric attenuation, and ground interactions); and source estimation (computation of equivalent noise levels at the source using corrected data). Backpropagation methods are particularly valuable for regulatory compliance and drone design optimization as they normalize noise measurements across diverse testing environments. Psychoacoustics explores how humans perceive sound beyond simple loudness, incorporating factors like sharpness, roughness, fluctuation strength, and tonal prominence. This field is particularly relevant for drone noise as it accounts for the human annoyance caused by specific sound characteristics, rather than overall noise levels. Psychoacoustic evaluations use controlled experiments where participants rate their reactions to recorded or simulated drone noise. These responses are then linked to psychoacoustic metrics through statistical models. Psychoacoustics measurements enable (i) the design of quieter drones by reducing tonal components and sharpness in propeller and motor designs; (ii) the development of regulatory standards by linking noise metrics to thresholds of human tolerance; and (iii) the development of targeted noise mitigation strategies based on the most irritating sound features. The main psychoacoustic metrics are defined as follows: loudness (measurement of the perceived intensity of noise, considering frequency weighting to reflect human hearing sensitivity); sharpness (quantifies the high-frequency content in a sound, often associated with harsh or piercing noise); roughness and fluctuation strength (assessment of rapid temporal changes in amplitude, contributing to public annoyance); and tonal prominence (identification of tonal components that stand out from background noise, often causing higher annoyance). Despite their advantages, psychoacoustic methods face challenges such as individual variability in responses and the need for well-controlled experimental conditions. Advanced computational tools are increasingly used to automate and refine these assessments, providing robust insights into drone noise perception. Noise directivity analysis studies how drone noise propagates in different directions based on

the drone's position, movement, and operating conditions. This approach uses directional microphones and advanced acoustic imaging technologies, such as beamforming arrays, to map noise patterns. Understanding directivity is critical in optimizing drone designs to minimize noise impacts in specific areas, particularly near sensitive environments like residential zones. However, these analyses are resource-intensive, requiring precise calibration, advanced equipment, and computational tools to process complex data. Surveys and subjective assessments collect human feedback on drone noise through field experiments or simulated environments. These methods provide valuable insights into the social and psychological impacts of drone noise [22]. For example, controlled exposure studies measure annoyance levels by varying drone operating conditions, while surveys capture public attitudes toward noise in real-world scenarios. Standardized questionnaires, such as the ISO 15666 annoyance scale [23], are often used to ensure consistency and comparability across studies. However, the reliability of these assessments depends on the sample size, diversity, and representativeness of the participant group. Recent studies [19] have integrated advanced technologies like machine learning and data fusion to improve drone noise assessment. These approaches combine telemetry data (e.g., drone location, speed, and altitude) with acoustic measurements to predict noise patterns dynamically. Additionally, remote identification systems mandated by aviation authorities, such as the FAA, provide real-time data streams that can enhance the accuracy of noise impact models. Each methodology contributes unique strengths to the study of drone noise. For instance, sound level meters and directivity analysis excel in providing precise technical data [19], while psychoacoustic evaluations and subjective surveys capture the nuanced human responses to noise. However, these approaches must be integrated to overcome their individual limitations and create a holistic assessment framework. Combining objective measurements with subjective insights ensures a more comprehensive evaluation of drone noise impacts. Figure A1a in Appendix A summarizes the main drone noise assessment methods along with their features and current limitations.

3. Human Factor and Noise Characteristics

Public acceptance of urban air mobility (UAM) depends on how noisy drones are for humans. People's perception of this noise is influenced by several elements, including the loudness, frequency, duration of exposure, environmental background, and individual physiological reactions. Designing quieter and more acceptable drone operations depends on an awareness of these features [24]. Among the most immediate and obvious elements influencing people's experiences with drone noise is loudness. The unique tonal components of drone noise can be considered disruptive even at rather low sound levels. This is because drone propellers produce a sharp, impactful sound that distinguishes them from broadband noise created by road traffic or other means of transportation. Measurements of how people perceive the intensity of these sounds are frequently performed using psychoacoustic models. A major source of annoyance, in addition to volume, is the frequencies found in drone noise. High-frequency tonal components produced by drone propellers stand out against background noise. These tonal peaks increase the annoyance and difficulty of ignoring drone noise. Spectral analysis is a common tool used by researchers to identify these frequencies and create strategies to reduce their consequences [25]. Communities' perceptions of drone noise are also influenced by the duration and frequency of noise exposure. Extended or repeated exposure might cause general annoyance, tiredness, and stress. Frequent, short bursts of noise can interfere with daily activities and decrease quality of life. Studies have modeled prolonged exposure situations to evaluate the total impact on mental health and output [7]. The perception of drone noise differs from that of other types of transportation noise. According to research, even when the total noise levels

are comparable, people react more negatively to drone noise than they do to helicopter, airplane, or traffic noise. Sound properties like sharpness and tonality, which intensify the perceived loudness and annoyance, are the cause of this discrepancy. Since their high-frequency, whirring sounds mimic insect-like buzzing, which naturally creates discomfort, smaller drones, such as the DJI Mini 3 Pro (DJI, Shenzhen, China), are frequently rated as more annoying, even though their overall noise levels are lower. The DJI Mini 3 Pro and DJI FPV (DJI, Shenzhen, China), two drones with smaller take-off weights and higher propeller speeds, received significantly more complaints than larger models according to a public study that looked at noise irritation from various drone types. Due to their more consistent sound profiles, larger drones such as the DJI M300 (DJI, Shenzhen, China) elicited lower irritation ratings, whereas the percentage of participants classified as "highly annoyed" (HAN) reached 22% for these smaller drones [24]. This discrepancy is mostly caused by the presence of tonal noise, which is especially invasive in the 1–5 kHz frequency range. These high-frequency tones are difficult to cover up with ambient noise, in contrast to broadband noise from traffic. Sharpness, a psychoacoustic property that gives a sound a more piercing or high-pitched quality, is another important component of drone noise. According to research, even when drones' actual sound pressure levels (SPLs) are lower than those of other noise sources, individuals nevertheless perceive them as louder when they have higher sharpness ratings. For example, even though the DJI Mini 3 Pro's (DJI, Shenzhen, China) SPL evaluations were similar to those of road traffic, people found it to be louder and more unpleasant [24]. In addition to the physical aspects of sound, perceptions of drone noise are also influenced by psychological variables. Drones tend to annoy people more when they are associated with privacy issues or unwelcome surveillance. However, individuals express less discomfort when drones are presented as helpful, such as when they are employed for emergency services or medical deliveries. The novelty of drone noise is another element; people are not used to the sound of drones yet because they are a relatively new presence in many places. This unfamiliarity can exacerbate annoyance, particularly in quieter suburban or rural locations with low background noise levels [9]. Additionally, people often perceive drone noise as being closer than it is, which further increases annoyance. This effect is most apparent during flyovers, when the sound variations carried on by movement convey a sense of intrusion and intensity. Researchers have performed offset analyses to measure the degree of annoyance caused by drone noise in comparison to other modes of transportation. These experiments demonstrate that drone noise only needs a slight change in volume (around +2, +3 dB) to match the annoyance level of helicopters and airplanes. However, drone noise needs to be much lower in volume (between −13 dB and −17 dB) than road traffic in order to be regarded as equally tolerable. This implies that drone noise is generally more annoying than broadband noise from automobiles and other ground vehicles due to its sharpness and tone peaks [24]. Different drone models' varying degrees of annoyance emphasize the significance of design elements such as the take-off weight, rotor configuration, and operational parameters like speed and altitude. Listeners find smaller, lighter drones more annoying because they typically create higher-pitched, inconsistent noises. The impact on communities can also be reduced by modifying flight levels and avoiding unnecessary low-altitude flyovers [24]. Another important consideration is the public's perception [25]. Reducing negative associations and perceived annoyance levels can be achieved by educating people about the advantages of drones and their uses.

Heavier drones typically produce more intense sound pressure levels (SPLs), which can contribute to higher perceived noise levels. Studies have found strong correlations between drone mass and perceived noise annoyance, particularly for quadcopters. Larger drones with a greater volume have more expansive acoustic footprints. Volume corre-

lates with noise emissions due to the size of propulsion systems and the increased drag and lift forces [13]. Single-propeller drones exhibit noise dominated by rotational blade dynamics, while coaxial propeller systems introduce additional tonal noise components due to interference and modulation between blades. Hybrid electric vertical take-off and landing (eVTOL) drones have shown lower annoyance ratings, likely due to optimized aerodynamic designs and quieter propulsion systems [26]. Propeller design significantly influences tonal noise characteristics. Drones with poorly optimized blade designs tend to exhibit sharpness and tonal peaks in their acoustic signatures, contributing to higher perceived annoyance. Multirotor configurations can lead to overlapping noise sources, creating complex sound fields that enhance certain psychoacoustic effects such as roughness and fluctuation strength [16]. Increasing the drone speed intensifies aerodynamic noise and may amplify broadband noise components. This is particularly evident during rapid maneuvers, where higher frequencies dominate the sound spectrum. Sound levels decrease with altitude due to spherical spreading and atmospheric absorption. However, lower altitudes result in higher SPLs and stronger annoyance perception due to proximity to listeners. Reference altitude corrections reveal that drones flying closer to receivers require significantly higher sound level adjustments to normalize measurements [27]. Hovering, take-off, and landing stages produce different noise characteristics. Hovering generates consistent tonal noise, while transitions such as take-off and landing involve fluctuating noise levels. Straight-line flight paths minimize abrupt changes in noise emissions, reducing perceptual annoyance compared to complex trajectories [24].

4. Assessment Framework

The comprehensive drone noise assessment framework proposed in this work is constituted by four main interconnected blocks (each one composed of other sub-blocks): drone design and optimization; operational factors; environmental and social factors; and noise metrics, data analysis, and policy integration. Figure A1b in Appendix A shows a schematic representation of the proposed framework.

- **Component Design**: Enhance rotor and propeller designs by optimizing blade pitch, geometry, and materials to reduce aerodynamic noise.
- **Weight and Size**: Minimize drone weight and dimensions to achieve lower acoustic signatures while maintaining functionality for specific tasks.
- **Aeroacoustics**: Address tonal and broadband noise components through advanced aeroacoustics modeling, improving noise directivity and reducing annoyance levels.
- **UAM Service**: Abstract information about the vehicle characteristics, flight stages, and operating and environmental conditions of the UAM service under consideration.
- **Path Planning**: Develop optimized flight paths that avoid densely populated areas and sensitive zones such as schools, hospitals, and parks. Incorporate real-time data on weather and airspace restrictions to adapt routes dynamically. Develop a comprehensive path planning framework considering both ground risks [28] and noise footprints [9]. In this sense, preliminary optimization can be achieved via metric-based planning of air corridors [29].
- **Velocity and Duration**: Implement speed adjustments to minimize noise propagation during critical flight stages. Optimize the operational duration to reduce cumulative noise exposure.
- **Mission Stage**: Focus on noise reduction during take-off, landing, and hovering, which are closer to receptor points. Investigate transition stages for smoother noise profiles.
- **Airspace Use**: Establish noise-sensitive zones and enforce altitude restrictions to mitigate community noise impacts. Leverage extended visual line-of-sight (EVLOS) and beyond visual line-of-sight (BVLOS) technologies to reduce proximity to receptors.

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- **Population Density Mapping**: Utilize GIS data to identify low-density flight paths for minimized human exposure to noise. Integrate urban and rural soundscapes to adapt operations based on location-specific requirements.
- **Urban Canyon Effects**: Model urban environments to predict and mitigate noise amplification caused by reflections and diffractions from buildings. Develop noise abatement strategies tailored to complex urban geometries.
- **Public Engagement**: Conduct community noise trials to gather feedback and refine operations. Incorporate perceptual metrics such as psychoacoustic annoyance models into planning and evaluation.
- **Energy-Based Metrics**: Quantify cumulative noise exposure with appropriate metrics such as the A-weighted equivalent continuous sound level (LAeq), LAeq over time period T (LAeqT), overall sound pressure level (OASPL), and sound exposure level (SEL). Measure noise directivity and spectral distribution to assess the noise impact comprehensively.
- **Perception-Based Metrics**: Evaluate sound quality metrics (SQMs) and psychoacoustic models for subjective noise annoyance. Investigate the correlation of noise perception and operational parameters.
- **Regulatory Compliance**: Align UAM operations with established standards, including LAmax thresholds for urban and rural contexts. Incorporate noise measurement protocols from ISO and other international guidelines.
- **Incentives for Quietness**: Encourage manufacturers to adopt quieter propulsion systems and noise-optimized designs through subsidies or tax benefits.
- **Community Standards**: Establish noise-sensitive operational hours and enforce restrictions in high-impact zones.

5. Concluding Remarks

In this paper, the latest findings in terms of drone noise assessment are discussed, including the characteristics of noise emissions, human annoyance, and noise emissions evaluation methods. Building upon this, a preliminary drone noise assessment framework for noise-aware UAM operations is proposed. Moreover, the need for further research on UAM noise is identified in the following areas: (i) the development of computational models to simulate noise propagation under varying operational and environmental conditions; (ii) the validation of models through real-world data collection; (iii) the investigation of the relationships between energy-based and perception-based metrics to develop a balanced evaluation framework; (iv) the development of new psychoacoustic models tailored to UAM platforms; (v) the development of a database of UAM acoustic signatures for different platforms, operations, and environmental scenarios; (vi) enabling data sharing among researchers, policymakers, and manufacturers for harmonized standards; (vii) the design of public surveys and noise trials to understand community concerns and acceptance levels; (viii) the exploration of the roles of visual and contextual factors in noise perception; and (ix) the development of emotion recognition models tailored to different UAM scenarios. In conclusion, by pushing the boundaries of the current technological, social, and regulation prospects, the noise-aware integration of UAM services in populated urban contexts is envisioned as a possible, yet still immature, option.

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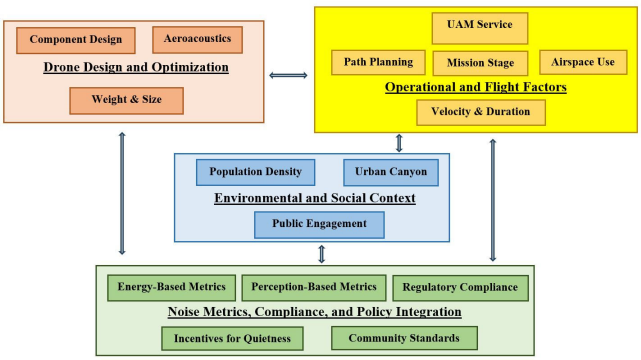
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Appendix A

Methodology	Overview	Feature	Limitation
Sound Level Meters	Measurement of noise SPL and frequency distribution.	Accurate and objective data on noise intensity.	Do not capture human perception/annoyance.
Back-Propagation Techniques	Estimation of source noise levels using corrections for environmental factors.	Standardized source-level noise characterization.	Require precise environmental data and advanced modelling.
Psychoacoustic Evaluations	Assessment of human responses to noise characteristics like loudness and sharpness.	Correlation of noise metrics and human annoyance.	Sensitive to individual variability and require controls.
Noise Directivity Analysis	Mapping how noise propagates in various directions.	Critical for design optimization and spatial noise control.	Resource-intensive and complex calibration required.
Surveys and Assessments	Collection of subjective responses from participants in controlled/real conditions.	Direct human feedback on noise impacts.	Results depend on sample size and representativeness.
Emerging Approaches	Use of machine learning and data fusion for dynamic predictions.	Integration of telemetry and acoustic data for real-time insights.	Require advanced computational resources.

(**a**)



(**b**)

Figure A1. (**a**) Critical overview of the main state-of-the-art drone noise assessment methods. (**b**) Schematic representation of the proposed noise assessment framework to inform noise-aware UAM operations.

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